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## **Relations between ac-dc components and optical path length in photoplethysmography**

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# Relations between ac-dc components and optical path length in photoplethysmography

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**Abstract.** Photoplethysmography is used in various areas such as vital sign measurement, vascular characteristics analysis, and autonomic nervous system assessment. Photoplethysmographic signals are composed of ac and dc, but it is difficult to find research about the interaction of photoplethysmographic components. This study suggested a model equation combining two Lambert–Beer equations at the onset and peak points of photoplethysmography to evaluate ac characteristics, and verified the model equation through simulation and experiment. In the suggested equation, ac was dependent on dc and optical path length. In the simulation, dc was inversely proportionate to ac sensitivity (slope), and ac and optical path length were proportionate. When dc increased from 10% to 90%, stabilized ac decreased from 1 to  $0.89 \pm 0.21$ , and when optical path length increased from 10% to 90%, stabilized ac increased from 1 to  $1.53 \pm 0.40$ . © 2011 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.3600769]

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## 1 Introduction

Photoplethysmography (PPG) is composed of a pulsatile component (ac) and nonpulsatile component (dc). ac is synchronized with the heart and related to arterial pulsation, while dc is related to light absorption in the tissue, vein, and diastolic arterial blood volume. dc has many physiological meanings and correlates with the ac waveform.<sup>1–8</sup> According to the Lambert–Beer (or Beer–Lambert) law that explains mechanisms of PPG, PPG ac is generated by the optical path length ( $\Delta d$ ) that changes with the increase of volume in blood vessels as they pulsate.<sup>9</sup> Therefore, it can be said that PPG ac is in a consistent relationship generated by variations in dc and  $\Delta d$ .

In previous studies of ac, dc, and  $\Delta d$ , there were correlations between continuous ac and spontaneous variations of dc,<sup>10</sup> but there has been no research on ac variation according to dc intensity. There have also been comparative studies of preop and postop blocking of sympathetic nerve systems or specific patients such as diabetics.<sup>3,11–13</sup> However, these studies only reported on experimental results and did not suggest a mathematical model that can explain the relationship between components, so they offer limited explanations of physiological results. Therefore, this study suggested an equation for the relationship between ac, dc, and components using the existing Lambert–Beer law to analyze the characteristics of PPG as a noninvasive vascular assessment tool. Results of the suggested equation were assessed through simple simulation and experiment.

## 2 Material and Method

### 2.1 Optical Model

Based on the Lambert–Beer law, the photodetector detects photons not absorbed into the blood. The waveform of general photoplethysmography used in many studies can be gained by inverting or subtracting the amount of light not absorbed at a constant ( $k$ ).<sup>3</sup> This is shown in Fig. 1, and the onset and peak of the photoplethysmography can be presented as Eqs. (1) and (2).<sup>14</sup>

$$I_H = I_O e^{-b_{dc} d_{dc}} e^{-b_{Hb+HbO_2} d_{min}} = \alpha \beta^{d_{min}} = k - I_{onset}, \quad (1)$$

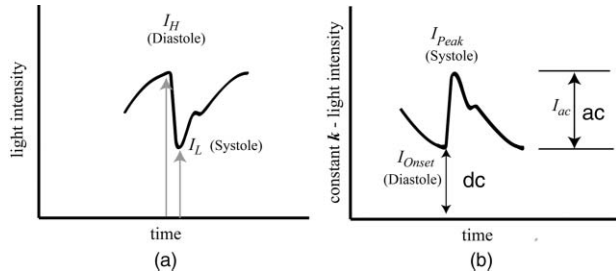
$$I_L = I_O e^{-b_{dc} d_{dc}} e^{-b_{Hb+HbO_2} d_{max}} = \alpha \beta^{d_{max}} = k - I_{peak}. \quad (2)$$

Here,  $I_L$  is the small value of reflected amount of light and the peak point of PPG.  $I_H$  is the large value of the reflected amount of light and the onset point of photoplethysmography.  $b_{dc}$  is a function of the absorption and the attenuation constants, and equation is  $b_{dc} = \varepsilon_{dc}(\lambda) c_{dc}$ .  $\varepsilon_{dc}(\lambda)$ ,  $c_{dc}$ ,  $d_{dc}$  each represent extinction coefficient, concentration of absorbing substance, and optical path length, respectively, that form extra-vascular photoplethysmography dc.  $\lambda$  stands for wavelength, and Hb and HbO<sub>2</sub> represent hemoglobin and oxyhemoglobin, respectively.  $d_{min}$  is the basal diameter of arterial vessel before pulsation and  $d_{max}$  is the maximum variation of arterial diameter during pulsation. The square of arterial diameter is proportionate to the amount of blood. If each  $\varepsilon$  and  $c$  are constant during a heart-beat,  $\alpha = I_O e^{-b_{dc} d_{dc}}$  and  $\beta = e^{-b_{Hb+HbO_2}}$  can be substituted into Eqs. (1) and (2).

PPG ac ( $I_{ac}$ ) is  $I_L - I_H$ , the subtraction of onset from peak, and is shown in Eqs (3), (4), (5), and (6) using variations in optic path length  $\Delta d (= d_{max} - d_{min})$ .

$$I_{ac} = I_L - I_H, \quad (3)$$

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**Fig. 1** Typical photoplethysmographic signal. (a) A raw signal measured from a photodetector. (b) Final signal, constant  $k$ -reflected light intensity.

$$= \alpha\beta^{d_{\min}} - \alpha\beta^{d_{\max}}, \quad (4)$$

$$= \alpha\beta^{d_{\min}} - \alpha\beta^{(d_{\min} + \Delta d)}, \quad (5)$$

$$I_{ac} = \alpha(\beta^{d_{\min}} - \beta^{d_{\min} + \Delta d}) = \alpha\beta^{d_{\min}}(1 - \beta^{\Delta d}) \\ = (k - I_{\text{onset}}) \cdot (1 - \beta^{\Delta d}). \quad (6)$$

According to Eq. (6),  $I_{ac}$  (a component of ac) is inversely proportionate to  $I_{\text{onset}}$ , proportionate to arterial diameter variation  $\Delta d$ , and has nonlinear characteristics.  $I_{\text{onset}}$  is a dc component of photoplethysmography and stands for nonpulsatile components and basal blood volume before pulsation.  $\Delta d$  is affected by arterial stiffness and generates  $I_{ac}$ . When Eq. (6) is transformed like Eq. (7),  $\Delta d$  can be estimated.

$$\Delta d = \text{abs} \left[ \ln \left( 1 - \frac{I_{ac}}{k - I_{\text{onset}}} \right) \right]. \quad (7)$$

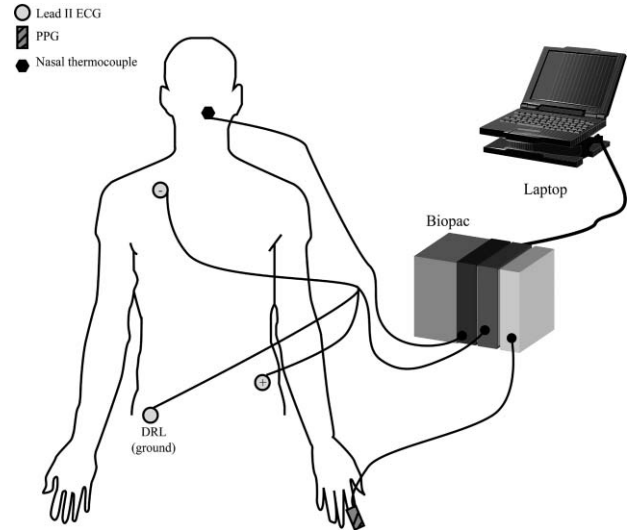
Numerical simulation was conducted to analyze the characteristics of ac components according to  $I_{\text{onset}}$  and  $\Delta d$ . Constant  $k$  was set up as 10 because signals voltage range of acquisition in the most commercial product for measuring biomedical data is  $\pm 10$  V.<sup>15,16</sup>  $I_{\text{onset}}$  increased in units of 0.001 from 0 to 10.  $\Delta d$  is converted approximately 0.04 mm when photoplethysmography is generated,<sup>9</sup> so it was increased from 0 to 1 mm in units of  $1 \mu\text{m}$ . The size of PPG ac calculated from each combination of  $I_{\text{onset}}$  and  $\Delta d$  was divided by the largest value, stabilized, and then analyzed.

## 2.2 Subject

A total of 20 subjects (15 male, 5 female, age  $23.1 \pm 3.4$ , BMI  $22.4 \pm 2.0 \text{ kg/m}^2$ ) who consented to the experimental objective and progress participated. Subjects did not have cardiovascular or respiratory disease and were prohibited from drinking alcohol, smoking cigarettes, and drinking coffee one day before the experiment.

## 2.3 Experiment

In this experiment, respiration, ECG, and PPG were measured for 5 min in the supine position, as can be seen in Fig. 2. All signals were measured using ECG100C, PPG100C, and SKT100C (BIOPAC System, Inc., Goleta, California), with a 1 kHz sampling rate. PPG was measured on the left index finger, and using



**Fig. 2** Experiment setting.

a TSD100 reflection-type sensor, it was set to  $20\times$  amplification in the 0.05 to 10 Hz bandwidth. ECG was used to identify the beat of PPG using a Lead II and amplified  $2000\times$  in the 0.5 to 35 Hz bandwidth.

Respiration was used to observe the rapid change in ac and dc due to deep inspiration, and it was measured via the Nasal method using a TSD202 sensor.<sup>17</sup> The experiment setting was maintained at room temperature.

## 2.4 Signal Processing and Analysis

The QRS of ECG was detected using the Pan-Tompkin algorithm.<sup>18</sup> Constant 10 was added to PPG to make a relative baseline with no negative voltage, and the onset and peak point of PPG was detected using the adaptive mood detection algorithm.<sup>19</sup> Noise was removed from respiration through an 11-point moving average filter. PPG beats with ECG beats, and no rapid changes in ac and dc due to deep inspiration were selected.  $\Delta d$  was derived from Eq. (5). dc and  $\Delta d$  were transformed from the 10<sup>th</sup> to the 90<sup>th</sup> percentile distribution for the characteristic analysis of ac, and the ac value was stabilized by dividing it with the mean ac value of dc 10th percentile. All signal processing was conducted using MATLAB (Mathworks, Natick, Massachusetts).

## 2.5 Statistical Analysis

All data were expressed as mean  $\pm$  standard deviation. SPSS (SPSS-IBM Inc, Chicago, Illinois) was used for statistical analysis. The ac characteristic curve was estimated using cubic regression (3rd polynomial regression). A  $p$ -value of  $<0.05$  was considered statistically significant.

## 3 Result

Figure 3 is a numerical simulation of stabilized ac characteristics with constant parameters (dc,  $\Delta d$ ) in Eq. (6). Figure 3(a) shows characteristics of ac components according to  $\Delta d$  when dc is constant. As the dc value increased, the ac slope (sensitivity) toward increase in  $\Delta d$  decreased. Figure 3(b) shows

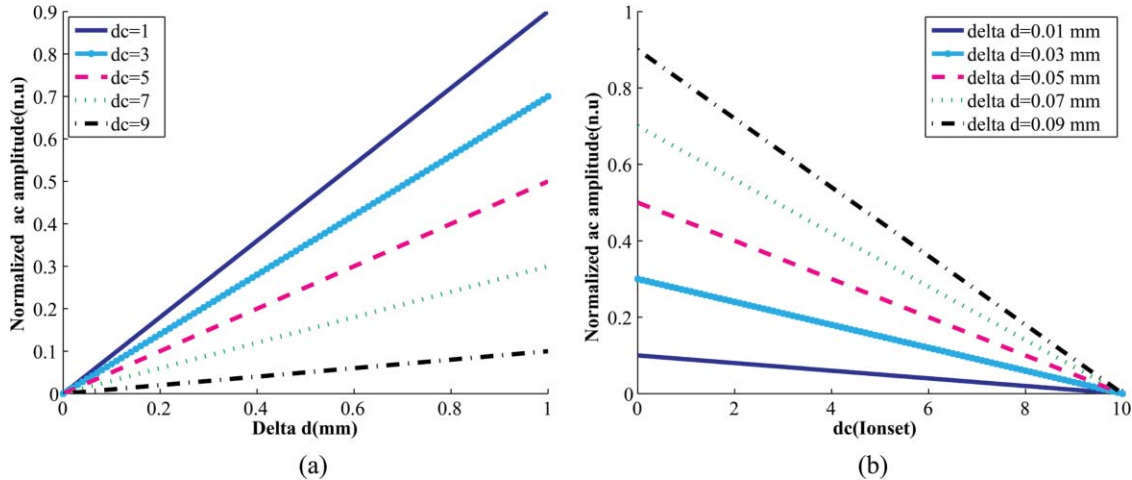


Fig. 3 Computed ac characteristics of proposed model equation. (a) ac- $\Delta d$  characteristics with fixed dc and (b) ac-dc characteristics with fixed  $\Delta d$ .

the response of ac component characteristics according to dc when  $\Delta d$  is constant. When  $\Delta d$  increased, the slope of ac raised in dc increased.

Figure 4 shows the ac characteristics according to dc and  $\Delta d$  percentile distribution obtained from actual experiment. In Fig. 4(a), when  $\Delta d$  was increased from the 10th percentile distribution to the 90th percentile distribution, stabilized ac increased from  $1 \pm 0$  to  $1.53 \pm 0.40$ . The curve fitting equation was  $y = 0.000001368x^3 - 0.00022x^2 + 0.01621x + 0.8627$  (adj.  $R^2 = 0.9997$ ,  $p < 0.0001$ ). In Fig. 4(b), when dc was increased from the 10th percentile distribution to the 90th percentile distribution, stabilized ac decreased from  $1 \pm 0$  to  $0.89 \pm 0.21$ . The curve fitting equation was  $y = -0.3898x^3 + 0.3028x^2 - 0.07596x + 1.009$  (adj.  $R^2 = 0.9273$ ,  $p < 0.0001$ ).

#### 4 Discussion

This study investigated ac characteristics according to the non-pulsatile component (dc) and optical path length ( $\Delta d$ ) to analyze characteristics of PPG components.

In the equation suggested to analyze ac characteristics, ac was dependent on dc and  $\Delta d$ . dc was inversely proportionate to ac, and  $\Delta d$  was proportionate to ac. Nonpulsatile components are related to tissue, vein, and diastolic arterial blood volume. Light absorption of other tissue, such as skin pigment, dye, and bone, were disregarded because it does not change according to blood flow, which means weak changes in continuous PPG signals.

From nonpulsatile components, venous capacity during respiratory change is connected to respiratory-induced fluctuation in the dc component, which is highly correlated to central and periphery venous pressure.<sup>1,6</sup> Venous capacity corresponds with venous return that affects blood capacity of the heart in each contraction. If venous tone is consistent in the venous return curve, venous return decreases with the increase in central venous pressure and decreases stroke volume. At this point, the autonomous nervous system increases heartbeat and arterial pressure to maintain homeostasis (maintain cardiac output).<sup>2,7</sup> PPG ac is proportionate to stroke volume, so when PPG dc is increased due to increase in central venous pressure, this increases arterial pressure, leading to a decrease in PPG ac components.<sup>2,7</sup>

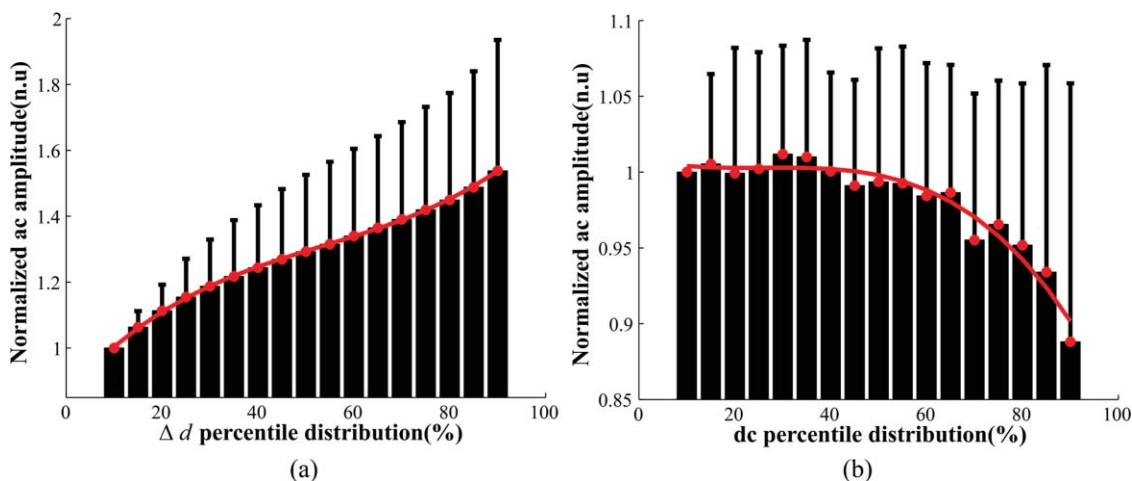


Fig. 4 ac characteristics by increasing  $\Delta d$  and dc percentile distribution. (a) ac- $\Delta d$  and (b) ac-dc.

The second nonpulsatile component in PPG is the arterial nonpulsatile component, which signifies the baseline blood capacity of the artery in contraction, and this baseline blood capacity is proportionate to diameter.<sup>20</sup> Arterial nonpulsatile components increase as arterial capacity or diameter increases. According to the stress-strain curve of the artery, the diameter is nonlinearly proportionate to blood pressure, and high blood pressure has high stiffness.<sup>20</sup> Therefore, an increase in arterial nonpulsatile components increases vascular stiffness, which then decreases ac. From the two cases above, ac decreases according to an increase in PPG dc shown in the proposed equation, and the experiment is in accord with existing physiological research.

ac characteristics according to dc and  $\Delta d$  generated transition characteristics starting from each median point. In experimental characteristics against dc, attenuation appeared differently at the 50th percentile, and as transition happened in  $\Delta d$ , ac increased. According to existing research,<sup>8,21</sup> on mechanical properties of normal subjects' peripheral blood vessels, as blood pressure increases, compliance and distensibility of the artery exponentially decreased with an inflection point, and diameter exponentially increases. Therefore, it can be concluded that the transition characteristics of ac shown in attenuation and an increase of experimental results follow the mechanical properties of blood pressure-diameter.

In conclusion, an equation to explain ac characteristics was suggested, and its dependence on dc and  $\Delta d$  was verified through a simple simulation and experiment. Our results may be utilized as a basic analysis tool for noninvasive vascular assessment.

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